NASA Conference Publication 2422

Applications of Tethers in Space

Executive Summary

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Proceedings of a workshop sponsored jointly by the Italian National Space Plan, CNR, and NASA and held in Venice, Italy
October 15–17, 1985

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1986

PREFACE

The Applications of Tethers in Space Workshop was held in Venice, Italy during the period October 15-17, 1985. The Hotel Excelsior, located on the island of Lido, provided outstanding accommodations for the workshop, which was jointly sponsored by the Italian National Space Plan, National Research Council, and the National Aeronautics and Space Administration, Office of Space Flight, Advanced Programs Division. Workshop coordination was provided by the Centro Internazionale Congressi and General Research Corporation. Aeritalia generously provided a gala dinner banquet for the workshop attendees and their guests, and the office of the Mayor of Venice hosted a reception at the city hall.

General Research Corporation would like to thank and commend everyone who organized, coordinated, and participated in the workshop. The panel co-chairmen are especially noteworthy in fulfilling their roles of directing and summarizing their respective panels. We are proud to have participated in the workshop and be a part of the advancement of this exciting and challenging field which, as is evident in these proceedings, is evolving into a technically sophisticated and mature science. The complete documentation of this workshop is contained in the Workshop Proceedings, Volumes 1 and 2. The Executive Summary, which contains an abbreviated compilation of the panel summaries, is also provided.

William A. Baracat
McLean, Virginia
March 1986

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FOREWORD

The Tethers in Space Workshop held in Venice, Italy, follows by only two years the one held in Williamsburg, Virginia, in June 1983. Yet, much has happened. The most significant events are: (1) the passing of our beloved leader, Giuseppe Colombo, (2) the announcement by President Reagan of the Space Station as a national goal, and (3) the initiation of several tether demonstration missions, already in hardware development or design phases.

Bepi, whom we call the "Father of Tethers," would be pleased at the pace of this emerging technology. The development of the Tethered Satellite System (TSS), a joint U.S. - Italy project, is on a firm course, with the first launch scheduled for 1988. The announcement of the Space Station goal by the President has provided an anchor for serious studies of the use of tethers on the Space Station. A whole panel session was devoted to this subject at this workshop, and was the second best attended. NASA, Italy, and industry continue to examine the benefits and technological problems associated with placing a tether system on the Space Station. We fully expect to see this happen, although it may be after the Initial Operational Capability (IOC).

Are there other tether and tether related missions that can be flown in the next few years on the Shuttle in addition to the TSS? The answer is yes. NASA, with Italy's involvement, will be verifying the principles of electromagnetic tethers in space to produce power or drag. A series of flight experiments are either hardware ready, or in hardware development. These experiments should enhance the TSS-1 mission, and may use at some point the disposable tether, which itself will require a preliminary demonstration. Looking to the future, there is much interest in the tethered platform, with the tether assisting in platform pointing. NASA's Ames Research Center, again with the Italians, are engaged in a definition study on this, called the Kinetic Isolation Tether Experiment (KITE).

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Our reach in this workshop has not only been to Earth orbit but also to the planets. Serious attention to tether operations near the Moon, Mars, and other planets is underway. Some of these ideas are presented in the workshop proceedings. Although it may sometimes seem that we are getting ahead of ourselves, these applications may be here sooner than we think.

Paul A. Penzo
March 1986

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I

ORIENTATION AND PURPOSE

Luciano Guerriero
PSN

It is a privilege and a pleasure for me to welcome such a qualified audience here in Italy and, in particular, the beautiful city of Venice, for this second workshop on the "Applications of Tethers in Space".

Two years ago, the first and very successful workshop on this subject was organized by NASA in the historical town of Williamsburg, Virginia. Now, I am really grateful to NASA and to my good friend Ivan Bekey, that they proposed to have this second workshop in Italy, and have offered to alternate between the USA and Italy for future editions of this meeting.

It is indeed a nice and friendly way to recognize the role and the efforts that Italy is providing to the development of the initial program and in the exploration of the full potential of tether concepts.

The choice of Venice has for me an additional important meaning: Padua University, 20 miles from here, one of the oldest in Italy and in the world, has for many centuries been the State University of the great and glorious Republic of Venice. From Padua University came Bepi Colombo, whose ideas have been of such exceptional importance for the development of the tether concept. It is very sad that Bepi, who has been friend and guide for many of us, is not with us anymore. However, I believe that your enthusiasm and your efforts to develop successful applications of the tether concept, is the best homage that can be attributed to his memory. Now we have to move into the program.

The Mayor of the city of Venice, Mr. Nereo Laroni, was expected to be with us. Unfortunately, he had to modify his schedule. We will meet him tonight, when he will host the reception at the City Hall. We are glad to have with us Mr. Salvadori, Assessore al Turismo, who will address the audience shortly, and officially open the meeting.

Sen. Granelli will then present the opening address. Sen. Granelli has the political responsibility for all Italian space activities. I must say that in Italy we are all very grateful to Mr. Granelli for this continuous and determined action in support of the Italian and European space programs.

I like to remember that, under his leadership as President of the Council of the European Space Agency, Europe has adopted very important decisions for the cooperation with the United States on the construction of the future space infrastructure in Low Earth orbit.

The present cooperation program between Italy and the United States on the Tethered Satellite System, and the perspective of a continuing cooperation on tether applications, have been strongly encouraged and supported by the Italian political authorities.

The presence of Minister Granelli at this meeting is certainly the best evidence of the Italian interest and commitment.

Two years ago, the first workshop on the Applications of Tethers in Space, held in Williamsburg, was very successful. At that time many interesting ideas were explored and evaluated.

During the past two years, while preparation of the first flight of the TSS was proceeding and taking us closer to the first and extremely important experimental test of the dynamic and electrodynamic properties of tether systems, studies on tether applications have been carried on, both in the USA and in Italy.

We would like to verify at this meeting what progress has been made, and to review together where we stand concerning:

- Theoretical and technical feasibility
- Cost effectiveness
- Constraints, in particular in connection with Space Station applications

- Preliminary design
- Possibilities for flight demonstration

We will try to maintain the organization of this meeting as close as possible to the one at Williamsburg.

Today we will have only a plenary session. We will start with a keynote address on the evolution of ideas on tether applications. This will be followed by a presentation on the status of the joint program on the TSS. A tutorial session on tether fundamentals and a survey of tether applications and technology will occupy the rest of the day.

In the second and third days the participants will be divided into working panels. The panel tasks are similar, but more ambitious, than the tasks set for Williamsburg. In particular, these tasks are:

- Identify additional new applications for tethers in space.
- Analyze, critique, and evaluate feasibility of all identified tether applications relative to their practicality, cost benefit, and operational requirements.
- Identify those critical design, performance, operational factors and technology advancements that must be included in the evolution of the practical feasibility of each tether application.
- Identify demonstration missions necessary to implement tether applications in space projects.
- Provide recommendations to NASA and PSN/CNR for the continued evaluation and definition of tether applications identified.

Plenary sessions in the afternoon of the second and third day will be used to present and discuss preliminary findings and recommendations. The panel co-chairmen are expected to product a final report document before leaving. Thank you.

II

PANEL SUMMARIES

SCIENCE APPLICATIONS

The panel took into consideration two different aspects pertaining to science applications: those having to do with the very first missions of tethered satellites, and those to be considered for a somewhat far-term future which imply new developments or new technology. Regarding the TSS-1 mission, the panel emphasized the need to consider the integrated character of the payloads which, in turn, requires careful attention to achieve full coverage of science. Understanding the electric and magnetic environment requires tethered satellites (or platforms) to be clean from the standpoint of electric and magnetic contamination to keep undesired noise below the expected level of significant measurements. Understanding the dynamics of the tether and improving atmospheric models are also essential goals, since accurate knowledge in this field is necessary to make possible some of the most interesting applications (among them, studies on gravity and geomagnetic anomalies) near Earth and/or to plan future advanced TSS missions or tether applications to space stations.

In particular, the panel felt appropriate to recommend all possible efforts to:

- improve the EMC/EMI properties of tethered satellites or platforms
- improve their DC magnetic cleanliness
- complement the payload with sensitive, low-power dynamical packages (accelerometer, tensiometers, etc.)
- stimulate close cooperation between dynamicists and aeronomists to get reliable dynamical and atmospheric models

Concerning the low altitude atmospheric missions, the panel discussed the broad areas of interest (listed in table 1) in connection with possible extensions to altitudes below approximately 130 km from the ground. Some possible experiments were presented, including measuring the concentra-

tion of atomic oxygen, by local measurements of resonant fluorescence at 130 nm using a lamp on TSS, as well as global density mapping of various ionospheric species utilizing bistatic LIDAR, based on triangulated photometric observations from TSS of a fluorescent column excited by a laser on the Shuttle. Table 2 summarizes the reasons of interest and challenges in the lowered TSS missions.

Concerning possible applications of tethers to Space Station, the panel heard the presentation by E. Anselmi on the Science Applications Tethered Platform. Although ideas have been set up by the geophysical and plasma communities, the apparently limited interest by the astronomical community was pointed out. The panel recommends that careful attention be devoted to investigating stability and pointing features of the platform, to check the possibility of using it for astronomical purposes.

The panel also devoted much attention to future scientific applications of tethered satellites. The development of tethered satellite technology offers exciting new possibilities for improved measurements on future solar terrestrial space missions. Tethered satellites suspended from orbiting space vehicles will be an excellent means for studying planetary atmospheres during future survey missions. Instruments at the end of long tethers may be used to collect samples during comet or asteroid rendezvous missions.

Concerning remote sensing from space, the concept of stereoscopic observations from tethered platforms for improved cartography has been further developed since the Williamsburg meeting. Two concepts have been analyzed. The first involves successive observations along the ground track using a solid-state array detector on a tethered satellite. The second consists of two synthetic aperture radars (SARs) placed vertically on a single tether.

Several ideas were discussed concerning future applications of tethers for basic scientific research. These included experimental

concepts for testing fundamental physical laws (unified field theories, general relativity, etc.), and the development of large aperture telescopes in space for improved astronomical viewing.

TABLE 1 - Broad Categories of Experiments for TSS-2

- o Ambient ion and neutral species
- o Electron, ion temperature and energy balance
- o Magnetic and gravitational field
- o Electric field
- o Electrostatic and electromagnetic waves
- o Stereoscope remote sensing of the Earth's surface
- o Dynamics of tethers (and satellites)
- o "Open wind tunnel" experiments at low altitudes

NOTE: Important developments are necessary in order for a tethered satellite to be deployed to lower altitudes.

TABLE 2 - Measurements Below 130 km

Interest:

- o Atmospheric transition from diffusive separation to turbulent mixture of components
- o Atomic oxygen to molecular oxygen
- o Shuttle and AOTV's major maneuvers occur here
- o Higher order terms of gravity and magnetic fields

Challenges:

- o Shock waves generated by a vehicle disturb the ambient atmosphere
- o Conventional instruments may not work (for example, mass spectrometers)
- o Measurement body (i.e., TSS) to be an aerodynamic body
- o New techniques to be developed (resonance and laser fluorescence, etc.)

ELECTRODYNAMICS

I. Introduction

Presented here is a summary of the Electrodynamics panel, integrated with significant conclusions from its three subpanels. These subpanels were: Electrodynamic Tether Power and Thrust Generation; Space Experiments and Demonstrations; and ULF/ELF/VLF Antennas, Signal Generation and Detection. Following this introduction are sections containing applications, issues and concerns, and flight demonstrations.

II. List of Applications

1) Multikilowatt to Megawatt Power and Thrust Generation: In the 1 to 20 kilowatt power range, recommendations were made to use electrodynamic tethers to provide contingency power for the Space Station, and to provide drag makeup and orbital maneuvering capability for Space Station and other solar array powered satellites, or for the power extension package (PEP) which could then be left in LEO orbit between successive Shuttle flights. Collection of current from the ambient space plasma might be accomplished with a passive collector in a low power system, or with a hollow cathode device, exploiting the low current regime of this device ($i \leq 3$ amp). In the higher power ranges, up to approximately one megawatt, recommendations were made for a Space Station energy storage system, short term high power applications and orbital maneuvering of the Space Station or other large space systems. Success in these areas is considered contingent upon the successful operation of hollow cathodes or related devices acting as plasma contactors (active collectors) with minimum loss. Early demonstration of device performance capability is an important component in the overall development of the electrodynamic tether.

2) Electrodynamic Tether ULF/ELF/VLF Antenna: Ground based detection of electromagnetic emissions from a tethered satellite system is an area of interest to communciations in the ULF/ELF VLF frequency ranges. In order to estimate signal detectability

at the receiver, information concerning signal characteristics (the transmitter), boundaries and propagation conditions (the medium), background noise statistical structure (in proximity to the receiver), and receiver characteristics are needed. Additionally, more advanced mathematical models than those presently in use are required for an adequate theoretical understanding of tether antenna systems.

3) Outer Planetary Missions

a) Jupiter Inner Magnetospheric Maneuvering Vehicle: The recommendation in this area was for a Jupiter inner magnetospheric survey platform to operate in the range from one to six Jovian radii. The electrodynamic tether in this application would be used primarily for orbital maneuvering operations.

b) Other Missions: Essentially, this area is an extension of the previous one to such regimes as exploration of the Saturn ring system, and beyond.

III. Issues and Concerns

1) Multikilowatt to Megawatt Power and Thrust Generation:

Specififally, the working panel made recommendations to:

- o Obtain voltage-current characteristics of plasma contactor devices operating at high tether currents (up to 50 amps).
- o Identify and understand the instabilities associated with such operations and their effects on system performance.
- o Better understand the ionospheric/magnetospheric current closure path and its associated losses.
- o Understand what effects operation of a large electrodynamic tether power/thrust generation system will produce in the LEO environment, and what impact these effects will have upon other space vehicles.
- o Assure long term tether insulator survival.
- o Understand effects of current collection at tether insulator defects and their impacts on system performance.

In addition to making these recommendations, a number of design trade-offs were identified including:

- **Shorter tethers operating at low voltage, high current might have advantages over longer tethers operating at high voltage, low current.**

- **Multiple cables connected in parallel (ribbon arrangements) might be preferable to single cables both in terms of length considerations (previous bullet) and in terms of resistance to damage by space debris (cable redundancy).**

- **Dynamics and control:**
  - **Counterbalancing tethers might be deployed in opposite directions from a spacecraft to provide center-of-mass-location control.**
  - **i l x B forces might be used for libration control provided that current phasing is correct.**

- **Power mangement, control and protection:**
  - **The electrical/electronic interface between the high voltage end of the tether and the user bus needs to be defined.**

2. <u>Electrodynamic Tether ULF/ELF/VLF Antenna</u>:

- **Characterize the propagation media including the ionosphere at LEO attitudes, the lower atmosphere, and ocean water (if submarine communication is the objective).**

- **Analyze sources of background noise and the statistical structure of that noise at the receiver**

- **Determine ground station locations for best signal-to-noise ratio transmissions including the possibility of mobile receivers.**

- **Correlate signals received at different ground station locations in order to subtract off noise.**

- **Characterize the instabilities and waves due to large current densities in the Alfven wings.**

- **Begin using warm plasma theory in analytical work.**

3. <u>Hollow Cathodes and Electron Guns - Comparison and Issues</u>: In order for the electrodynamic tether power/thrust generation concept to be viable, it is necessary to make electrical contact with the ionosphere at both ends of the tether. Contact may be made in a number of ways including use of a passive, conducting subsatellite (as is the case with TSS-1), use of an electron gun, or use of a plasma generator (such as a hollow cathode or hollow cathode based device). The working panel concentrated on

hollow cathode type plasma generator devices and specifically made recommendations to:

- o Perform laboratory and analytical characterization of plasma diffusion, double sheaths, magnetic field effects and contact impedance.

- o Develop high current plasma contactor technology with max. electron currents of 50 amps and ion currents of 2 amps.

- o Fly a hollow cathode on the Shuttle Orbiter for the TSS-1 mission. This will: demonstrate critical contactor technology; ensure the Orbiter is clamped at a potential near local space plasma; and prevent unintentional, differential, high voltage charging of the Orbiter surfaces.

- o Fly hollow cathode based plasma contactors on both ends of the tether for future TSS electrodynamic missions.

IV. Flight Demonstrations And Applications

1) Plasma Motor Generator Proof of Function (POF) Flights: Three candidate missions were identified in this area to explore hollow cathode versus passive electron collection from the ionosphere, il x B deflections of the tether, use of tether ballast with a simple deployer and high current delta-V dynamics. The first mission involves use of a 200 m conducting tether with hollow cathodes at both ends of the tether, a variable biasing capability and currents no more than 0.1 amp. The second mission involves a 2 km tether with hollow cathodes at both ends and currents up to 5 amps, while the third mission uses a 10 km tether and currents up to 50 amps.

2) Choice of Early Missions: The missions in this area will use electrodynamically generated power levels of 1 to 20 kilowatts, and will demonstrate capability for drag makeup and orbital maneuvering of Space Station and other large space systems.

3) Longer Term Missions: The missions in this area will use electrodynamic power levels up to one megawatt with ULF/ELF/VLF antenna applications and planetary missions in mind.

TRANSPORTATION

The transportation panel has discussed the following applications and has ranked them. The ones having the best potential near-term payoffs are listed first. The rest depend increasingly on future developments, either in tether technology itself or in the remainder of the space infrastructure.

1. Shuttle expendable tether system for boosting payloads from the Shuttle (SETS). Initially, expendable tethers were considered in conjunction with the external tank of Space Shuttle. Since less than 1 lb. tension is needed to downward deploy the external tank, low tension deployment captured attention. A proposal for a study resulted. Deploy-only mode for expendable tethers with low (but not zero) tension means you do not need a take-up capability. The system that results is a low-tension high-braking capability system that can be used to deboost payloads by a pendulum swing release. A project to launch a 50 lb. payload from a GAS can is in the initial hardware development stage, and could fly before TSS. SETS has been approved for experimentation.

Critical Issues:	Priority: Near Term, High Recommended Flight Tests:
- Operations	- In works
- Hardware	- Deboost
- Safety	- Preferred for 1st test
- Reliability	

2. Electrodynamic propulsion of tethers for transport, including small and large orbit changes within LEO

Critical Issues:	Priority: Near Term, High Recommended Flight Tests:
- TSS one mission & success of other early tests	- TSS-1 and other plasma contactor experiments needed
- IMPORTANT Value of electrodynamic propulsion is considered to be of such high priority that all possible methods should be looked at during early tether tests	
- Dynamics of orbital elements	

3. Tethered OTV operations to reduce the delta-V needed to reach GEO. OTV is considered a Space Station element. OTV tether boost combined with stage and propulsive burn is the concept. Hanging and swinging tether options being considered, and Shuttle, E.T., and Space Station as

launch mass options. Relative payload gains noted for all three OTV options: reusable; air propulsive; reusable aerobraked; or expendable (in decreasing order). Swinging tethers offer improved capabilities over hanging tethers without noticeable penalties. Expendable tethers are preferred over reusable tethers. Command and Control issues examined.

3A. Tether Boost Technology Demo Package. Using a Centaur to demonstrate potential to augment OTV deployment by tether. Demo in 1990s. After Centaur returns to LEO by aerobrake, it would rendezvous with Orbiter for tether demo. Called Centaur and Shuttle Tether (CAST) tether demonstration package.

Critical Issues:	Priority: Near Term, High
- Shuttle based v. Space Station launch	Recommended Flight Tests:
--- maximize commonality	- Centaur & Shuttle Demo Shuttle Demo
- Attitude Control of end mass	- TSS-1 & Other Electrodynamic (Plasma experiments)
- Release operations of end mass	
- TSS vs. expendable tether	
--- TSS Robust but instrumented	

4. Tethered docking and release of Shuttle with Space Station. Results in slightly lower apogee, much lower perigee, tethered deboost, and propellant scavenging (for transfer to an OMV).

Critical Issues:	Priority: Near Term, High
- Space Station SCAR design impact	Recommended Flight Tests:
- Operation precision	- Can be demo by SETS or TSS
- Temporary S.S. orbit effects	- Capture
- Loads on Space Station	

5. Low RPM spinning tethers for artificial gravity for manned planetary excursions.

Critical Issues:	Priority: Near Term, High
- Can it also be used in LEO?	Recommended Flight Tests:
--- Proof of concept	- Some TSS-1 data applicable
- How much gravity is needed by human physiology?	- TSS-1 in a spin mode - Future TSS or SETS experiments
- Can it be Shuttle/TSS tested? Concept demonstration during TSS mission one or two?	

6. Multiple-pass aerobraking tethers for planetary orbiters to simplify navigation. Using 100 km, 1 mm dia. tether hanging from a 2000 kg space probe circularized above a planet with an atmosphere, to reduce orbit height Saves mass over a "hard shield" aerobrake.

Critical Issues:
- Material options
- Scheduling/control options
- Meteoroid risk
  --- Ribbon is better?
  --- Multiple strands
- Failure
- Dynamics for tether
  --- Elliptical orbit?
- How deep into atmosphere do requirements of science want probe to go?
- Flow fields
- Specular vs. diverse flow

Priority: Near Term, High
Recommended Flight Tests:
- SETS or TSS II Demo
- TSS II should yield data applicable

7. Use of series of equatorial plane tethers as a stairway to escape velocity

Critical Issues:
- Need equatorial or polar plane launch
- Nodes vs. Van Allen Belt

Priority: Later Development
Recommended Flight Tests:
- Other flight experiments should cover

8A. Spinning tethers to pick up lunar material.

Critical Issues:
- Dynamics
- Releasing-aiming-catching (especially core grabber)
- Deployer hardware
- Mass concentrations - lunar

Priority: Later Development
Recommended Flight Tests:
- Ground based tests
- TSS should be considered

8B. Lunar-surface based sling. Launching 10 kg payloads, by a rotating sling on the lunar surface. An Apollo lander sized vehicle lands and anchors itself to the lunar surface. A rover retrieves materials and passes them to the anchored sling, which throws 10 kg into lunar orbit. A lunar orbital tether station then slings payload into a lunar-Earth transfer.

Critical Issues:
- Could it be scaled and tested in a vacuum chamber?
- Does this have a customer? Are lunar materials needed?
- Bearing loads

Priority: Later Development
Recommended Flight Tests:
- Ground tests (vacuum)

- Release mechanisms
- Can they be caught?
- "Safety" issues
- Shape of spinning tethers
  Dynamics?
- Manufacturing techniques
  for tapered tethers

8C. Rotating constellation with a center reel, to be used to sling material from asteroid belt without landing

Critical Issues:
- Basic design
- On asteroid or in space?
- Release, aiming, etc.

Priority: Later Development
Recommended Flight Tests:
- Ground tests

8D. Rotating hoop of tether material, under magnetic field to reduce tension, to be used as a method of slinging material from lunar surface

Critical Issues:
- Super-magnetic technology
- Supplement the tensile properties of the material
- Dynamics
- Releasing-aiming-catching (especially core grabber)
- Deployer hardware
- Mass concentrations - lunar
- Electrical energy
- Throughput potential

Priority: Later Development
Recommended Flight Tests:
- Ground tests seem in order
- Further examination

CONTROLLED GRAVITY

During its deliberations, this Panel formulated a significant class of opportunities that the panel denoted as "controlled gravity." This capability offered by tether systems has unique aspects that seem not to have been fully appreciated or articulated previously. These topics reach to the very foundations of fundamental science and still have immediately apparent practical possibilities. In the experience of the Panel members this is a rare and precious circumstance deserving serious and careful attention.

Tether systems offer the new possibility of controlled acceleration fields, or controlled gravity, in the range from 10^{-1}g to values below 10^{-6}g, perhaps even 10^{-8}g. Tether systems achieve their control through placing experiments at significantly large displacements from the orbit center or zero acceleration position of an orbiting system. The system may either be in a gravity gradient stablilized configuration (rotating once per orbit in an inertial frame), or it may be rotating more rapidly. Controlled, as used here, includes not only the magnitude of the acceleration field, but also its vector properties, time dependence, and the uncertainty or noise associated with them. For example, by varying the length of a tether with a prescribed control law, a desired time dependent acceleration field can be imposed on a system. This changing field could be a step function of varying magnitude, a periodic function, or some other pattern.

Biological response to different fixed magnitudes of gravity or to varying acceleration fields is a topic of significant interest. In the range from 10^{-1}g to 10^{-8}g, little is known about threshold values for biological phenomena. Measuring these is a fundamental scientific contribution, and also has implications for extended space missions such as a manned expedition to Mars. Is some level of artificial gravity necessary or desirable during such a trip? If so, what level is required or optimum? These issues could be explored on tethered platforms in orbit about the Earth. If necessary, a mission to Mars could employ a rotating tethered configuration to supply the desired artificial gravity.

Fluid mechanics play ubiquitous roles in space operations ranging from propellant handling to separation of organic molecules. A tether system can be applied beneficially to many of these. However, in many cases the optimum acceleration field is just not known. How sensitive is the product to noise or other unwanted variation of the field? Do important thresholds exist? Such questions can be answered definitively only if experiments can be done with different controlled acceleration fields.

The answer to these optimization and threshold questions can have important fiscal implications both for anticipated commercial operations and for facilities such as the Space Station. The imposition of an unnecessarily restrictive acceleration requirement on the Space Station can be very costly. On the other hand, refurbishment to correct for inadequate initial requirements is also costly. Tether systems can facilitate answers to these questions and provide a versatile mechanism for control of the acceleration field within the Station.

An additional implication of a tether for controlled gravity is the isolation it provides from disturbances. A tether acts as a low frequency bypass filter to lateral disturbances, while work with tether weaves may also provide some damping of disturbances along the tether. As an example, a microgravity laboratory could be attached via tether to the Space Station in order to isolate it from disturbances.

When more complex, or constellation configurations of three or more bodies are examined, controlled gravity is a natural consideration. Perhaps the first example of this class will be an elevator mechanism that attaches to the tether between two primary bodies and carries a third body upward or downward along the tether. The acceleration field in the third body thus can be easily controlled by moving it up or down the tether.

RECOMMENDATIONS

TERMINOLOGY

Microgravity	10^{-4}g and smaller	reduced gravity
Low Gravity	10^{-1}g to 10^{-4}g	reduced gravity
Earth Gravity	1 g	
Hypergravity	greater than 1 g	enhanced gravity

Figure 1

The first recommendation of the panel was the terminology presented as Figure 1. The Panel was asked to organize its conclusions and recommendations as they pertain to three eras: 1) the Tethered Satellite System period extending through the first few TSS flights, 2) the period of Space Station Initial Orbital Capability embracing its first few years of operation, 3) a post-IOC period when the Space Station becomes mature and facilities are added systemataically to it. The recommendations, presented in Figure 2, also include a priority list of tether uses and of economical demonstrations of tether capabilities. Controlled gravity uses or objectives that the Panel judged to be appropriate for each era and the demonstrations and experiments that would address these objectives also appear.

	TSS ERA PRE-IOC	IOC ERA FOR SPACE STATION	POST-IOC ERA
OBJECTIVES AND USES	Objective is to master the concept and technology of gravity control. Gravity control would be applied to: Life Sciences Materials Science Fluid Science Engineering Uses	Gravity Controlled experimentation in Space Station applied to: Life Sciences Materials Science Fluid Science Engineering Uses	Fully exploit gravity control in Space missions.
DEMONSTRATIONS AND EXPERIMENTS	Demonstrate gravity profile generation, measurement and use, including appropriate analysis and evaluation. Recommended Opportunities for early demonstrations: Spinning Orbiter Mission Orbiter experiments during tether missions Elevator on a tether.	Science and application experiments, possibly using TSS deployer	Processes and applications.

Figure 2

The demonstrations during the TSS era described below fall in two general classes: 1) gravity-stabilized tethered systems, and 2) rotating systems.

Disposable Deployer Mission, (1987). This mission may allow a measurement of the acceleration field change and particularly the associated acceleration noise at positions in the Shuttle while the tether and payload are deployed. Appropriate instrumentation for these measurements needs to be identified and scheduled for the mission.

Spinning Shuttle Mission, (1987-8). This mission provides the first opportunity to begin investigations of controlled gravity and threshold phenomena in the low gravity range (10^{-1} to 10^{-4}). Although a tether is not involved in this demonstration, the rotation principles for achieving low gravity are the same as for a rotating tethered system. Fluid science and applications are particularly pertinent for this mission. Necessary instrumentation and demonstration equipment should be planned.

TSS-1, (1988). The resulting acceleration field on the Orbiter including the associated acceleration noise, should be correlated with other data such as accelerations on the satellite, tether length, and tether tension. This mission should provide the necessary information to extrapolate performance of a tether gravity system for Space Station.

TSS-2. The controlled gravity experiments on the Orbiter for TSS-1 should be repeated and expanded. This mission may provide an opportunity to test an "elevator" that moves along the tether.

KITE. The disturbance isolation aspects of this proposed mission may make it particularly suited to studies of the uncertainties or noise levels that accompany the obtained acceleration fields.

TSS-3. The controlled gravity objectives for this mission would be similar to those for TSS-2, except that improved demonstrations should be expected based on experience with earlier missions.

CONSTELLATIONS

I. Introduction

The Constellations Panel shared its life during the Workshop with both the Controlled Gravity and Space Station Panels. Tethered constellations, in fact, can provide a valuable solution to projects such as the micro-g/variable-g laboratory, the multi-probe tethered system, and the centrifuge for low-gravity applications. The following presentation highlights the versatility of tethered constellations and the various configurations that have been conceived. The presentation is divided into three time frames which have, as a central reference point, the IOC (Initial Operating Capability) phase of the Space Station program. Therefore the demonstration flights of certain one-dimensional tethered constellations belong to the Pre-IOC-Era while the final, operational utilizations of the one-dimensional tethered constellations belong to the IOC-Era. All the other new or more complex configurations have been listed under the Post-IOC-Era category. A listing of these various configurations are presented in Table 1 and Figure 1, with attributes of selected configurations shown in Table 2.

II. Conclusions

1-D vertical constellations provide unique capabilities (1st priority)

- 3-mass system (space elevator) can provide variable-g environment from microgravity level to 10^{-2}g.
- More-than-3-mass system provides simultaneous data collection at different locations.
- 3-mass system (SS in the middle) for SS orbital center management allows simultaneous micro-g experiments and other tether assisted experiments.

2-D constellations (2nd priority)

- Stable configurations proposed for providing a separation of functions among physically connected platforms.
- Pseudo-elliptical constellations provide an external 2-D frame for stabilizing light structures (reflectors, solar sails).

III. **Recommendations**

- Improve fidelity of the dynamics models.
- Multi-function tether concept to be further developed
- Tether physical characteristics; effects on the system dynamics
- Ingenious design of crawling systems
- Improve knowledge of micro-g/variable-g requirements

TABLE 1 - Applications Divided by Era

Pre-IOC-Era

1. Demo flight for the micro-g/variable-g (space elevator) with a modified TSS system (e.g., adding a down-scaled elevator to the TSS)
2. Shuttle-borne, multi-probe 1-D system for simultaneous data collection (e.g., measurement of spatial geophysical gradients with good time correlation)

IOC-Era

3. Micro-g/Variable-g Lab (space elevator) Space Station-borne
4. Space Station c.o. (orbital center $\simeq$ center of mass) management
5. Space Station-borne multi-probe system

Post-IOC-Era (All of these are free-flying systems)

6. Quadrangular 2-D constellations electrodynamically stabilized
7. Quadrangular 2-D constellations stabilized by differential air drag
8. Pseudo-elliptical 2-D constellation, electrodynamically stabilized
9. Centrifuge for low-g application: $>10^{-3}$ g
10. Torquing of a spinning station (or vehicle) for controlling the precession rate of the spin axis.

Figure 1 - Constellations

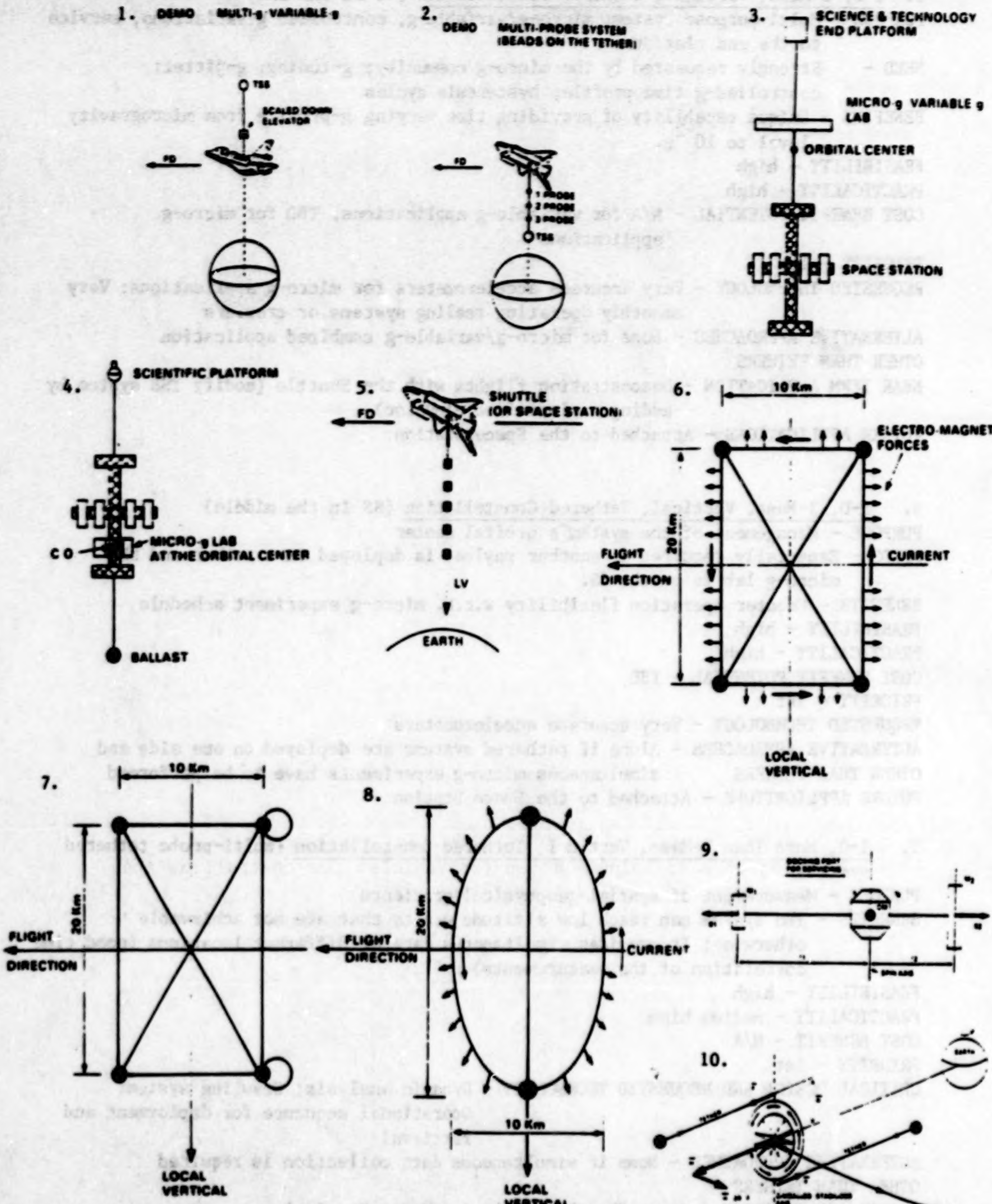

Table 2 - Attributes of Selected Configurations

3. 1-D, 3-Mass, Vertical, Tethered Constellation (SS at one end)

PURPOSE - Multi-purpose system: micro-g/variable-g, controlled g variations, service to the end platform

NEED - Strongly requested by the micro-g community; g-tuning; g-jitter; controlled-g time profile; hysteresis cycles

BENEFITS - Unique capability of providing time varying g-profile from microgravity level to 10^{-2}g.

FEASIBILITY - high

PRACTICALITY - high

COST BENEFIT POTENTIAL - N/A for variable-g applications; TBD for micro-g applications

PRIORITY - 1st

REQUESTED TECHNOLOGY - Very accurate accelerometers for micro-g applications; Very smoothly operating reeling systems or crawlers

ALTERNATIVE APPROACHES - None for micro-g/variable-g combined application
OTHER THAN TETHERS

NEAR TERM APPLICATION - Demonstration flights with the Shuttle (modify TSS system by adding a simplified elevator)

FUTURE APPLICATIONS - Attached to the Space Station

4. 1-D, 3-Mass, Vertical, Tethered Constellation (SS in the middle)

PURPOSE - Management of the system's orbital center

NEEDS - Especially required if another payload is deployed on a tether and the micro-g lab is on the SS.

BENEFITS - Greater operation flexibility w.r.t. micro-g experiment schedule

FEASIBILITY - high

PRACTICALITY - high

COST BENEFIT POTENTIAL - TBD

PRIORITY - 1st

REQUESTED TECHNOLOGY - Very accurate accelerometers

ALTERNATIVE APPROACHES - Alone if tethered systems are deployed on one side and
OTHER THAN TETHERS simultaneous micro-g experiments have to be performed

FUTURE APPLICATIONS - Attached to the Space Station

5. 1-D, More Than 3-Mass, Vertical, Tethered Constellation (multi-probe tethered system)

PURPOSE - Measurement of spatial geophysical gradients

BENEFITS - The system can reach low altitude orbits that are not achievable otherwise; It provides simultaneous data at different locations (good time correlation of the measurements)

FEASIBILITY - high

PRACTICALITY - medium high

COST BENEFIT - N/A

PRIORITY - 1st

CRITICAL DESIGN AND REQUESTED TECHNOLOGY - Dynamic analysis; Crawling system; Operational sequence for deployment and retrieval

ALTERNATIVE APPROACHES - None if simultaneous data collection is required
OTHER THAN TETHERS

FUTURE APPLICATIONS - Space Shuttle flight (or Space Station)

Table 2 - (continued)

6. **2-D, Electrodynamically Stabilized Constellation** (ESC)
PURPOSE - Separation of junctions in a physically connected configuration
FEASIBILITY - medium
PRACTICALITY - with complexities
PRIORITY - 2nd
CRITICAL DESIGN - Multi-reel system control; Better dynamics analysis required
FUTURE APPLICATIONS - TBD

7. **2-D, Differential Drag Stabilized Constellations** (DSC)
PURPOSE - Separation of functions in a physically connected configuration
FEASIBILITY - Medium
PRACTICALITY - With complexities
PRIORITY - 2nd
CRITICAL DESIGN - Multi-reel system control; Better dynamics analysis required
FUTURE APPLICATIONS - TBD

8. **2-D, Electrodynamically Stabilized, Pseudo-Elliptical Constellation** (PEC)
PURPOSE - External frame for stabilizing light structures (e.g., reflectors, solar sails)
FEASIBILITY - High
PRACTICALITY - Medium high
PRIORITY - 2nd
CRITICAL DESIGN - Multi-reel system control
FUTURE APPLICATIONS - TBD

TECHNOLOGY AND TEST

Early definition of the enabling technologies and the initiation of programs required to resolve the tether related technology issues is critical to the success of the TSS program as well as the growth and maturing of the tether concept. This report attempts to define these technology issues, as well as a technology based application and several systems concepts requiring technology development.

Technology Issue — Tether Requirements/Materials/Configuration

The panel felt that the definition and development of tethers is the singular most critical technology related to the implementation of the tether applications defined to date. It is imperative that the tether characteristics/requirements necessary to accomplish the various proposed applications be defined. The definition of potential tether environments and the development of tethers that are compatible with that environment is critical. Issues such as temperature, atomic oxygen, ultraviolet and infrared radiation, and micrometeoroid impact, must be defined and addressed. High temperature tethers capable of operating under large loads at temperatures in excess of 1000° K must also be investigated as well as the requirement to be conductive for power or data transmission.

Another critical design consideration is the incorporation of tether system redundancy. Instrument capability that would detect tether failure and provide early warning for system safety is recommended for design and definition.

As a result of these issues, the Technology and Test panel recommends that (1) NASA and PSN initiate a coordinated program to define tether requirements and a development and test program to evaluate tether concepts and materials, (2) that a Tether Requirements/Materials/Configuration panel be established for the next workshop to generate interest and activity in the area.

Technology Issue -- Tether Dynamics

It is believed by the panel that the development of accurate dynamic simulation/mission modeling capabilities is critical to the acceptance of the tether concept. It is imperative that the dynamic characteristics of TSS-1 and TSS-2 be accurately predicted to ensure the acceptance of the concept. The panel expressed concern that there are numerous special purpose simulation capabilities in existence and the number is growing at what seems to be an exponential rate. The panel is also concerned of the inability to generate a test case for evaluation of the various dynamic models, including Skyhook and GTOSS. As a result of the panel concerns, it is recommended that the existing Tether Dynamics Working Group's activity be expanded to include the design, development, implementation, and review of a dynamics "test case" incorporating the TSS-1 and TSS-2 missions for program verification. The Tether Dynamics Working Group should oversee this. As with the Tether Requirements/Materials/ Configuration issue, the establishment of a Dynamics panel for future workshops is recommended.

Technology Issue -- TSS-2 Supporting Technology Programs

There are several TSS-2 related technology issues which concerned the Technology and Test panel, namely: instrumentation, materials, aerothermal analysis, dynamics, and satellite configuration.

The issue of instrumentation relates to the design and development of both the mission control instrumentation; such as, tensiometers, which the panel recommends at each end of the tether for all TSS missions for dynamic control and post-flight verification, and tether temperature sensing for mission control and tether performance verification as well as science related instrumentation. Relative to the science instrumentation, it is important to note that the TSS-2 mission will operate in a region of the upper atmosphere that imposes peculiar measurement requirements to define molecular species and determine ion and electron concentration at both the satellite surface as well as across the flow

field; i.e., Mass Spectrometer and Rayleigh Scattering (laser systems), respectively. Finally of concern was the development of heat flux sensors for the satellite and the tether, and the need for instrumentation capable of detecting tether failure.

The panel was also concerned about tether and satellite materials. Since the panel is interested in extending TSS-2's operating range (below 130 km altitude), studies relative to both tether and satellite materials that will perform at higher temperatures are recommended. Aerothermodynamic data resulting from these studies will result in requirements for considerable studies relative to tether/satellite dynamics as well as mission studies relative to the deployment, mission operations, and retrieval of the tethered system, specifically relative to communication, tracking and satellite/tether control.

Finally, the panel expressed concern relative to the mission turnaround time between TSS-1 and TSS-2 and the lack of compatibility of the objectives of TSS-1 and TSS-2 satellite configurations. It is believed that such delays will considerably compromise the success of the first mission and thereby the potential growth of the concept and its applications for Space Station particularly. Consideration should, therefore, be given to the development of two satellites--one for electrodynamic missions and one for atmospheric missions. The primary recommendation relative to TSS-2 is the initiation of detailed system studies to define the present mission limitations required to extend the present TSS capablity to lower altitudes.

Technology Issue — Shuttle Tethered Aerothermodynamic Research Facility - STARFAC

This is the Technology and Test panel's proposed tether application. STARFAC is a research proposal that would take advantage of the tether concept's peculiar capability to provide in-situ steady-state aerothermodynamic/atmospheric data. The proposal recommends the extension of the TSS-2 capability to an altitude of 90 km. While present studies indicate that a passive TSS-2 configured satellite may be limited to 100 km altitude, the inclusion of negative lift, propulsion, or tether con-

figuration changes, could extend this capability. Supporting technologies as discussed relative to TSS-2 are: Instrumentation, Materials, Configuration, and Dynamics/Mission Design. Studies should be initiated as soon as possible on mission design and limitation definition, as well as the development and test of required hardware systems with emphasis on instrumentation and high temperature components.

<u>Technology Issue -- TSS-1/Electrodynamic Technology</u>

For the future of the electrodynamic tether concept, the development of tether conductors and insulators is critical. It is recommended that tether materials recieve priority study with significant emphasis on electrodynamic applications. Finally, the success of the electrodynamic tether concept depends on the generation of power in kilowatts which requires the development of high voltage power management and control hardware. (See Electrodynamic panel's report for details on this as well as recommendation for a hollow cathode to be flown on TSS-1.)

<u>Technology Issue -- Space Elevator (Crawler)</u>

The implementation of many tether applications requires the development of a tether crawler for tether inspection but primarily for the transport of materials and equipment between a Space Station, for example, and a tethered work station. The panel encourages continued design effort relative to the Space Elevator (Crawler) concept.

<u>Technology Issue -- Tether Pointing Platform</u>

The Tether Pointing Platform is a system proposed by both NASA and Aeritalia for various applications relative to tether controlled operational missions. The Technology and Test panel recommends continued study of this concept, feasibility definition and demonstration.

<u>Technology Issue -- Time</u>

The Technology and Test panel is concerned relative to the timely definition and development of the application's enabling technologies. The development of these technologies must be accomplished as soon as possible to allow the evolutionary growth of the tether concept.

SPACE STATION

INTRODUCTION AND GENERAL BACKGROUND

It has not happened very often in space flight that a long dormant but radical new element of space flight is about to appear at the scene of space operations. The last several years have seen the advent and growth of a new avenue to space utilization: the tether. This report is structured to cover the general and specific roles of tethers in space as they apply to NASA's planned Space Station.

The evolution of the tether concept into an engineering program is phased with the growth of the Space Station program. In such a way there is the possibility to have the tether applications compatible with the Space Station configuration and/or to be aware of what kind of tether related operations have to be eliminated due to evident conflict with respect to the Space Station requirements. In addition, the results of system investigation/dynamic studies/simulations and, later on, flight demonstration through the first TSS mission are major drivers for tether concept application, particularly to the Space Station. The major final goal is to have tether concept application in conjunction with the IOC-phase Space Station. In that regard, after having assured/verified the compatibility with the Space Station configuration, the associated benefits should automatically facilitate any final decision. It is anticipated that total or partial demonstration is required in order to complete the technical and safety scenario. The major hope is that the impacts on the Space Station configuration can be easily accommodated. That can more probably become a reality if the specific issues are approached as soon as possible and in the most proper way.

TETHER APPLICATIONS TO SPACE STATION IOC ERA (priorities will vary with program changes)

	Tethered Orbiter Deployment (with OMS Propellant Scavenging)
	Tethered Launch of OTV
IOC	Tethered Space Station C.G. Vernier (C.G. Management)
IOC	Electrodynamic Reserve Power
IOC	Electrodynamic Thrust (Drag Make-up)
IOC	Tethered Platform (short mission)
IOC	"Zero G" Laboratory (soft suspension)

IOC Tethered Elevator (soft suspension)
Remote Docking of Orbiter
IOC Deboosting Small Cargo Modules
IOC Electrodynamic Tether (Research)
Tethered Propellant Depot and Fuel Transfer
Tethered Antenna Farm
IOC Multi-Probe (beads on string)(short mission)
Remote Wake Shield

SPACE STATION BENEFITS FROM TETHER APPLICATIONS

- "Zero G" Laboratory
- Reserve Power Generator
- Halve Orbiter Deboost Propellant Requirement With Tether Deboost
- C.G. Management
- Waste Disposal by Tether
- Quick Sample Return
- Eliminate OMV Propellant Tanker by Scavenging OMS Propellant During Tether Assisted Orbiter Deorbit
- Eliminate Instrument Contamination Via Tethered Instrument Modules
- Transfer of Hard Point For MRMS/Tether Operations From Orbiter to SS
- Platform Useful to Settle Materials Before Processing
- Periodic Supply of OMS Bi-Propellant for OMV and Platforms
- Reduction of Stationkeeping Propellant Deliveries
- Reduced Reqmts for De-Orbit Logistic By Tethered Waste Disposal
- Tether Assisted Attitude Control (Contamination Reduction)
- Combination of CM Control Antenna Farm, Tether Assisted Attitude Control and Collision Avoidance Maneuver Capability by a Specific Tether System (Deployed Mass)
- Maintenance of Constant Altitude for Earth Observations
- Utilization of Power Surge Caused by Orbiter Deployment for Material Melting Coincident with the Generated G-Field for Settling the Melt
- Tether is the Only Way to Maintain and Exercise Control Over Various Variable Gravity Fields (10^{-2} to 10^{-5}) and Thus Responding to an Urgent Scientific Requirement (Evolution of Gravity Maps)

FLIGHT DEMONSTRATIONS

- Tether Shape Measurements
- KITE/Scaled-SATP
- Disposable Tether System Verification
- Fluid Transfer Experiments Under Various DC and AC Accelerations
- Existing Experiments to be Repeated Under Different G-Levels.
- Needed: Tether Mediated Rendezvous Demonstration
    - P/L Deployment and Subsequent Retrieval

- o Elevator/Crawler Demonstration (Gravity Field Mapping and Perturbation Determinations)
- o Verifying and Refining Dynamic Models in Flight Demos
- o Attachment/Detachment of Crawler to Tether Using RMS, EVA
- o Drive Mechanism for Crawler, Either Electromechanical or Electromagnetic
- o Variable/Minimum Gravity Demonstrating Accuracy and Duration
- o Attitude Control for Rotation About Tether and Stabilization for Instrument Pointing
- o Power Generaton/Dissipation
- o C.G. Location and Maintenance for P/L's and Experiments on Crawler
- o Degree of Automation/Robotics
- o Internal Suspension System

REQUIRED TECHNOLOGY EMPHASIS

- o Tether Technology including: Materials and Configurations, Maintainability, Tension Control, Damping Characteristics, and Environmental Compatibility
- o Deployer Technology, especially Motor/Generator and Motor/Reel Coupling
- o Electrodynamic Technology: Plasma Contactors, High Voltage Insulation, High Voltage Conversion and Control, Specific Tether Construction, and Environmental Compatibility
- o Engineering Instrumentation
- o Science Instrumentation
- o Critical Systems Hardware (Mechanisms, Devices, etc.)

SPACE STATION CONFIGURATION AND OPERATION ISSUES AND CONCERNS

- o Space Station Collision Avoidance Maneuvers Require 20 km Displacement in any Direction and Up to 24 Hours Notice
- o Space Station Quiet Periods Up to 30 Consecutive Days (10^{-6} g)
- o Proximity Operations
- o Debris Collision Probability of Long Duration Platform Tether
- o Platform May Have to be Retrievable Without Tether
- o Manned Zero G Laboratory
- o High G Levels During Orbiter and OTV Deployment (10^{-2} g)
- o Zero G Tether Module Also Used as Transportation to Platform
- o On-Board Zero-G Laboratory Quite Massive (25,000 kg)
- o Platform May Have to Have An Autonomous Power System because Electrical Tethers Introduce Perturbations
- o Energy Supply and Dissipation for Elevator
- o Tethered Fuel Facility Has Severe Operational Problems
- o Thrust Generation Due to Punctured Tank Cannot Be Handled
- o Reqmt to Support 20 KN Longitudinal Force By SS Structure

SPACE STATION TETHER APPLICATIONS PRIORITIES

The Criteria for the following priorities were IOC Space Station applicability, improved operational capability, and the solution to Space Station problems

- **Variable Gravity Laborabory (Controllable)**
- **Deboosting Small Cargo Modules**
- **Electrodynamic Reserve Power**
- **Tether Space Station C.G. Control (Vernier)**
- **Tethered Orbiter Deboost**
- **Tethered Remote Docking of Orbiter**
- **Tethered Science/Applications Platform**

FUTURE TETHER APPLICATIONS

A. Other Potential Tether Facilities in Earth Orbit
A-1 Electrodynamic OMV and Debris Collector
A-2 Spinning Facility for Simulating Lunar and Martian Gravity
A-3 Spinning Transport Node near GEO

B. Potential Lunar, Martian, and Asteroidal Tether Facilities
B-1 Surface-Based Slings (on the Moon, Phobos, and Asteroids)
B-2 Transport Node in Low Lunar Orbit (See Figure 2)
B-3 Space Station in Low Mars Orbit

CONCLUSIONS AND RECOMMENDATIONS

- **Tethers can uniquely accomplish the Space Station basic objectives**
- **Tether applications can solve significant Space Station problems**
- **Tether applications can greatly improve Space Station capabilities and operational efficiencies**
- **Tether dynamics requires better understanding and more research**
- **Tether applications should be incorporated into Space Station design for use at IOC**

III

WORKSHOP SUMMARY OF RECOMMENDED APPLICATIONS AND DEMONSTRATIONS

The Friday morning session of the Applications of Tethers in Space Workshop in Venice included the panel co-chairmen, and was devoted to listing those applicatons which would be appropriate for various eras.

Some discussion was also devoted to demonstration and TSS missions, which would provide high science return and/or proof of an operational capability. This input is provided in outline form only. Detailed discussion of most of these applications may be found in the proceedings, or the attached references.

Shuttle Era

1. Small Payload Placement
2. Electrodynamic Power Supply
3. Multiprobe (Constellation) System
4. Open Wind Tunnel
5. Gravity Controlled Experiments

Space Station IOC ERA

1. Variable Length Tether for Space Station C.G. Management
2. Electrodynamic Power Supply
3. Electrodynamic Thrust (Drag Makeup)
4. Tethered Platform (Short Term Missions)
5. "Zero G" Laboratory using a Tethered Elevator
6. Deboosting Small Cargo Modules
7. Electrodynamic Tether for Research
8. Multi-probe "Beads on String" Constellation

Space Station Post IOC Era

1. Tethered Orbiter Deployment with OMS Propellant Scavenging
2. Tethered Launch of OTV
3. Remote Docking of Orbiter
4. Tethered Propellant Depot and Fuel Transfer
5. Tethered Antenna Farm
6. Remote Wake Shield

Post IOC - General

1. Spinning Manned Facility
2. Tethers on Platforms
3. Electrodynamic OMV
4. Remote Aerobraking
5. Two Dimensional Constellations

6. Station in LEO to Capture Launch Vehicles in Suborbital Trajectories (LEO Node)
7. Higher Orbit Tether Transfer Nodes
8. Rotating Tether (Sling) attached to the Moon or an Asteroid to Eject Surface Material into Orbit
9. Tether Facilities at other planets

In addition to these applications, some discussion was given to demonstration missions and their candidate objectives. The following are somewhat in chronological order of development.

A. Plasma Motor Generator (McCoy - 86; frequent reflights are planned)

- o Demonstrate feasibility and performance of hollow cathode
- o Dynamics and temperature response
- o Pulse effects on ambient plasma
- o KU-Band radar tests

B. Disposable Deployer (Carroll - 87; frequent reflights are planned)

- o Test successful release of tether
- o Vibration dynamics
- o Aerobraking effects of tether
- o Aerothermal effects using balloon
- o Tether recoil and shape
- o Conduct low gravity experiments on Orbiter during tether deployment

C. Spinning Orbiter with Tethered Satellites

- o Test fluid settling and slosh
- o Conduct low-gravity science

D. Tethered Satellite System (TSS-1)

- o Accurate dynamics verification
- o Data collection for other applications
- o Passive electron/ion collection efficiency
- o Effectiveness of hollow cathode on Orbiter
- o Test accelerometers on Orbiter
- o Test tensiometers on satellite
- o Satellite passive retrieval mode for backup

E. Shuttle Released Dumbell Satellite

- o Test rendezvous feasibility
- o Dynamic behavior
- o Elevator attachment

F. Tethered Centaur

- o Test feasibility

G. Kinetic Isolation Tether Experiment (KITE)

- o Pointing stability and accuracy
- o Disturbance isolation
- o Test extension cord concept
- o Do low gravity experiment on Orbiter

H. Tethered Satellite System (TSS-2)

- o Planned aerodynamic experiments
- o Low gravity on Orbiter
- o Possible elevator test

I. Tethered Satellite System (TSS-3; see also TSS-1 applications)

- o Plasma contactor on Orbiter and satellite
- o Test spin mode

<table>
<tr><td>1. Report No.
NASA CP-2422</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Applications of Tethers in Space - Executive Summary</td><td>5. Report Date
May 1986</td></tr>
<tr><td>6. Performing Organization Code
MT</td></tr>
<tr><td colspan="2" rowspan="2">7. Author(s)
William A. Baracat, Compiler</td><td>8. Performing Organization Report No.</td></tr>
<tr><td>10. Work Unit No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Advanced Programs Division
Office of Space Flight</td><td>11. Contract or Grant No.
NASW-3921</td></tr>
<tr><td>13. Type of Report and Period Covered
Conference Publication</td></tr>
<tr><td colspan="2">12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546</td><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes
William A. Baracat: General Research Corporation, McLean, Virginia.</td></tr>
</table>

16. Abstract

The proceedings of the second workshop on Applications of Tethers in Space, sponsored jointly by the Italian National Space Plan, CNR, and NASA, held in Venice, Italy, October 15-17, 1985, are summarized here. The workshop was attended by persons from government, industry, and academic institutions to discuss the rapidly evolving area of tether applications in space.

Many new applications were presented at the workshop, but, more important, existing applications were revised, refined, and prioritized as to which applications should be implemented and when. The workshop concluded with summaries developed individually and jointly by each of the applications panels.

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<tr><td colspan="2">17. Key Words (Suggested by Author(s))
tethers
microgravity
electrodynamic tethers
space shuttle
space station
tethered satellite system</td><td colspan="2">18. Distribution Statement
Unclassified - Unlimited

Subject Category 37</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
44</td><td>22. Price
A03</td></tr>
</table>

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1986